

The Neutron 'Thunder' Accompanying Large Extensive Air Showers

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The bulk of neutrons which appear with long delays in neutron monitors nearby the EAS core ('neutron thunder') are produced by high energy EAS hadrons hitting the monitors. This conclusion raises an important problem of the interaction of EAS with the ground, the stuff of the detectors and their environment. Such interaction can give an additional contribution to the signal in the EAS detectors at km -long distances from the large EAS core after a few μs behind the EAS front.

1. Introduction

The dispute on the role of low energy neutrons as the possible origin of delayed ('sub-luminal') pulses in the neutron counters and scintillator EAS detectors has begun long ago [1,2,3,4]. However, the observed delays did not exceed a few μs . The present work has been inspired by the observation of the multiple neutrons which followed extensive air showers with delays as long as *hundreds* of μs [5,6,7,8,9]. Such delays have been observed with the Tien-Shan neutron monitor for EAS in the PeV energy region. Later this finding has been confirmed by other experiments [10,11,12,13,14] and the existence of the effect is now beyond any doubts. There is, however, no agreement about its origin [14,15,16]. Briefly the essence of the effect is the appearance of the numerous neutrons delayed by hundreds of μs after the passage of the main shower disk in the vicinity of the EAS core. In the spectacular scenario of 'the thunderstorm model' this phenomenon has been compared with the thunder which appears with a delay after the lightning during the thunderstorm [17].

2. The PeV energy range

In the detailed study [8] of the effect it has been claimed that the process has a threshold and the delayed neutrons appear at PeV primary energies, i.e. in the region of the 'knee' observed in the primary energy spectrum. Another observation

is that these neutrons are concentrated within a few meters around an EAS core and accompanied by delayed γ -quanta. All these features let the authors assume that this phenomenon is connected with the properties of high energy (PeV) interactions [16].

The other groups [14,15] attributed the effect to the low energy physics, i.e. explained it by neutrons which are produced inside the neutron monitor by numerous nuclear scatterings and disintegrations, caused by hadrons in the EAS core and which then propagate outside the core region. Some of them appear also as albedo neutrons from the nuclear cascade developing in the ground underlying the neutron detectors after EAS propagate from the air into the ground. This explanation has been based on their own experimental data.

In [18] we presented arguments based on our simulations at PeV energies which give support to the latter explanation. Simulations of the EAS neutrons have been also made in [19]. If our interpretation of the effect is true, the scenario of 'the neutron thunder' complements our knowledge of the EAS development and its interaction with the ground, surface detectors and their environment. Like in the case of the transition effect, in which some part of invisible gamma-quanta is converted into electrons or electron-positron pairs in thick scintillator or water cherenkov detectors this effect demonstrates that our records depend on our detectors. Within this scenario another problem appears - the production and propagation of neutrons created when the EAS core hits the ground.

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Due to their long propagation length [20] these neutrons can give observable effects both at shallow depths underground, in particular at mountain altitudes where the EAS cores are more energetic, and also as albedo neutrons - in surface detectors. Due to the slow diffusion of thermalized neutrons their contribution to the signal in the detectors is relatively high at large delays after the main EAS front. There might be plenty of other interesting effects worth of the experimental and theoretical study. In this paper we discuss the possible consequence of the effect for the large EAS arrays built for the study of cosmic rays (CR) at EeV energies.

3. The EeV energy range

In the light of the possible contribution of neutrons to the signal in water and ice cherenkov detectors used in many experiments, viz. Pierre Auger Observatory (PAO), MILAGRO, NEVOD, Ice-Top and others, we have made simulations of EAS in EeV energy range similar to those made at PeV energies [18]. The interaction model is the same QGSJET-II, but the observation level is that of PAO, i.e. 1400 m a.s.l.. The primary proton has 1 EeV energy and the vertical incidence angle, the electromagnetic component has been simulated using EGS4 option with the thinning level of 10^{-5} .

The lateral distribution of electromagnetic component ($e^+ + e^- + \gamma$), muons ($\mu^+ + \mu^-$) and neutrons is shown in Figure 1. I stress that neutrons simulated here are *not* secondary neutrons, produced by EAS in the ground, but are those produced within EAS in the air. The γ -quanta are included into the electromagnetic component since the water tanks of PAO are thick enough to absorb them and to get the contribution to the signal. Both distributions of the particle's number and energy are shown. The separation of PAO water tanks is 1.5 km. It is seen that *if* neutrons are absorbed in the water and their energy is transformed into the visible light they could contribute up to 10% to the signal at such large distances.

It should be remarked that neutrons at large distances from the EAS core have mostly the en-

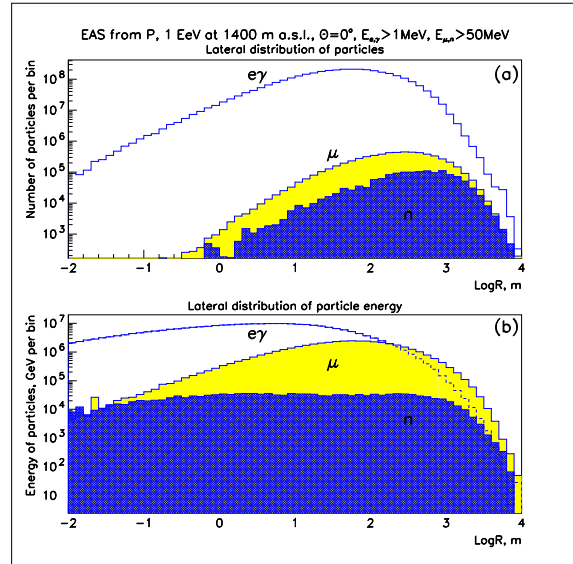


Figure 1. Lateral distribution of particle's number (a) and the particle's energy (b) for 1 EeV primary proton incident vertically at the level of 1400 m a.s.l. It is seen that neutrons could contribute up to 10% to the signal of water tanks at 1km distance from the shower axis, if there are relativistic electrons among products of their interaction with water.

ergy below a few GeV and a very wide, nearly isotropic angular distribution. Their delays with respect to the shower front spread up to tens of μs . Interestingly, neutrons create two distinct groups with energies above and below $\sim 10^2$ GeV. Apparently such separation is the consequence of different production mechanisms: neutrons above 10^2 GeV are secondaries produced in high energy hadron collisions, lower energy neutrons appear mostly in knock-on processes. It is neutrons of the first group which carry the bulk of hadron energy together with other hadrons in the EAS core. They create γ - and hadron families in X-ray films and ensure the subsequent multiplication process in the neutron monitor. The neutrons of the second group diffuse with a non-relativistic speed and with a wide angular distribution to the periphery of the shower where they can give delayed 'sub-luminal' pulses in the scintillators.

The temporal distribution of the particle's number for electromagnetic, muon and neutron component at distances $R < 10\text{m}$, 100 and 1000 m from the core is shown in Figure 2. It is seen that after $5\mu\text{s}$ at the core distance of 1km neutrons are the dominant component of the shower. Such distances and times are typical for the detectors of PAO. However, neutrons are neutral particles and at these distances they are non-relativistic, therefore they cannot emit cherenkov light directly. Only if in the process of their moderation and thermalization in water they create relativistic electrons and γ -quanta, they can be detected. In fact such processes do exist, viz. an excitation of oxygen nuclei with the subsequent emission of γ -quanta or $n + p \rightarrow d + \gamma$ reaction. The experiment at Tien-Shan confirmed that neutrons create such gamma-quanta in the surroundings of the neutron monitor [8]. As for water tanks, such a possibility has to be checked experimentally. In any case the contribution of neutrons into the signal of water cherenkov detectors should be estimated and taken into account in the conversion of $S(1000)$, the EAS particle's density at 1000m from the core, into the primary EAS energy.

4. Discussion and Conclusion

In 1928 Niels Bohr formulated his 'complementarity principle'. It means that it is impossible to observe both the wave and particle aspects of atomic physics simultaneously. In other words it implies that only certain information can be gained in a particular experiment. Some other information that can be equally important cannot be gained simultaneously and is lost. This is exactly the situation with the study of EAS. It is a complex phenomenon and so far different detectors observe and study different EAS components: Geiger counters - charged particles, mostly electrons, thick scintillators are sensitive also to some part of gamma-quanta, gamma-telescopes - cherenkov light, ionization calorimeters - an electromagnetic and hadron component and X-rays - highest energy part of these components. Neutrons are neutral particles and so far they were not studied separately from all other hadrons. It is a merit of Chubenko A.P. and his colleagues

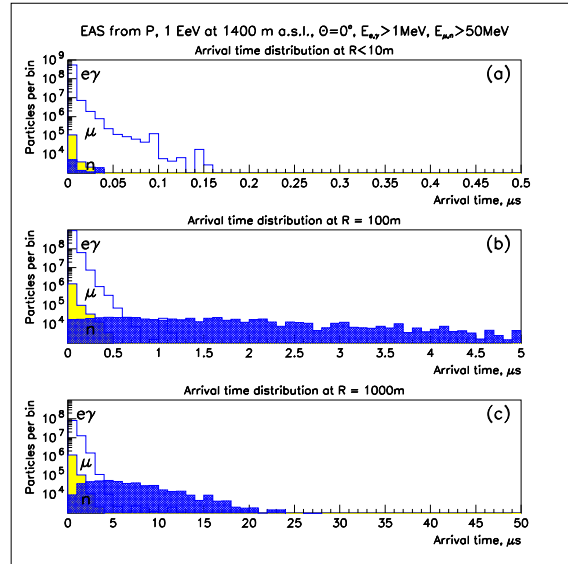


Figure 2. Arrival time distribution of electromagnetic, muon and neutron component of the shower at core distances less than 10m (a), 100m (b) and 1000m (c). It is seen that at 1000m from the core neutrons dominate among other particles after $5\mu\text{s}$ delay.

who applied the neutron monitor for the detailed study of the neutron component of EAS. The neutron monitor is the detector which includes the polyethylene as the moderator and reflector - the hydrogen containing material, which increase the sensitivity of the device to neutrons. Chubenko A.P. et al. discovered the 'neutron thunder' - neutrons delayed up to ms after the passage of the main shower front. Although according to our interpretation the bulk of the observed neutrons have a secondary origin, i.e. they are produced and delayed inside the monitor, the existence of the neutrons produced within EAS and accompanying the main shower front is now without any doubt. The true 'neutron thunder' associated only with EAS is not so long as that observed inside the monitor - the simulations show that it can last up to hundred ns . However neutrons of EAS can definitely cause the same effects in the environment, in the ground and in the detectors

as they make in the neutron monitor, like an 'echo effect', which lasts up to hundreds of μs .

First of all it is particularly true for the studies at the mountain level where the EAS core as the neutron's producer is more energetic, than at sea level. Secondly a good part of the year the ground at the mountain level is covered by such neutron moderator as snow (Tien-Shan, Aragats, Chacaltaya, South Pole) sometimes a few meters thick. Snow As for the Tien-Shan station there might be an additional factor emphasizing the role of neutrons - its ground is a permafrost with a good fraction of ice inside.

As for the detector sensitivity to neutrons, water and ice tanks are particularly worth of attention. First of all water is also a moderator. Secondly, although the neutrons cannot produce cherenkov light directly, the study [8] showed that they produce gamma-quanta and electrons, which can be eventually detected by water tanks due to their emission of cherenkov light. Since water and ice filled detectors are wide spread all over the world and in particular used in the PAO, the contribution of neutrons to their signals at large distances from the EAS core and at large delays from the trigger time, can be substantial. It should be analysed and taken into account if necessary. The same remarks could be referred to hydrogen containing plastic scintillators used in many other large EAS arrays (Yakutsk, Telescope Array etc.).

In any case the phenomenon of 'the neutron thunder' complements our knowledge of the EAS development and is certainly worth of the further experimental and theoretical study.

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